Renewable and Sustainable Energy Reviews 28 (2013) 643–653

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

On the management of wind power intermittency

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ARTICLE INFO

Article history:
Received 5 April 2013
Received in revised form
1 August 2013
Accepted 11 August 2013
Available online 4 September 2013

Keywords:
Wind power management
Wind power intermittency
Renewable energy resources (RESs)

ABSTRACT

Nowadays, the world is encountering severe challenges in the energy generation sector. Environmental issues like climate change, global warming and Green House Gases (GHGs) and also social issues like dramatic increase in global population and increasing energy demand are the main causes of global concerns about energy resource management. In this regard, Renewable Energy Sources (RESs) are the suitable substitution to replace the conventional generating units that emit GHGs due to the use of fossil fuels. Among all RESs, wind energy seems to be promising for generating emission-free electrical energy. However, it is naturally unpredictable due to its intermittency which leads to some technical problems such as generation imbalance as well as optimal reserve allocation. This paper investigates the solutions to compensate wind intermittency through introducing various technologies such as Pumped-Hydro Storage (PHS) units, Plug-in Hybrid Electric Vehicles (PHEVs), solar energy and other electric storages like batteries.

Contents

1. Introduction

In recent years, the increase in world population as well as energy demand leads to more consumption of fossil fuels such as petroleum, gas, coal and drives non-renewable energy sources to produce electric energy. The increasing demand in fossil fuels definitely causes environmental pollutions such as Green House Gases (GHGs) like CO_2, SO_2, NO_x etc., leading to air pollution. In order to prevent air pollution, the one but the most important factor is to reduce the CO_2 emission quickly by determining the emission sources by all countries. The CO_2 emission propagation all around the world is increased during the most recent years and

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http://dx.doi.org/10.1016/j.rser.2013.08.034

fossil fuel consumption leads to annual increase in CO_2 emission by 3.4% between 2000 and 2008. However, this rate is about 1% as reported in 1990s. In order to reduce emission, more sustainable energy sources are required [1]. According to the predictions performed by scientists, if the current progress on petroleum reserves discovery and consumption proceeds, the petroleum reserves will finish by the year 2038 [2]. The burning of fossil fuels causes to acidy rains and global warming. Accordingly, policies toward more secure, clean and sustainable energy must be established to meet the increasing energy demand. The demand-increase occurs in developing countries and it is predicted that energy demand would increase by 55% in 2030, causing fossil fuels consumption to be about 84% and also increase in GHG emission of about 57%. It is estimated that in such conditions, 16 million tons of CO_2 will be emitted to the atmosphere [3,4]. The global concerns about the emissions and climate change become a serious debate since 1990. In Iran which is a developing country, from 1967 to 2007 the fossil fuel consumption has been increased by 617% leading to increase CO_2 emission propagation by 610% [5]. As it can be observed from Fig. 1, some countries like China and U.S. generate the highest amount of emissions, especially CO_2 emission compared to others. If these countries were committed to the international agreements, such as Kyoto protocol, the problem of climate change and global warming would be definitely improved [6].

Nowadays, energy is a key factor to reach the stable economy and improve the social welfare in all countries [7]. The energy demand is increasing in almost all countries wherein governments' target is for reliable electric energy [8]. The global energy consumption met 11,428.1 Mtoe (million tons of oil equivalent) for which 88% was provided using fossil fuels [9]. This value reaches 12,274.6 Mtoe by 2012 [10]. Fig. 2 shows cumulative diagram of global energy consumption for different conditions during past decade.

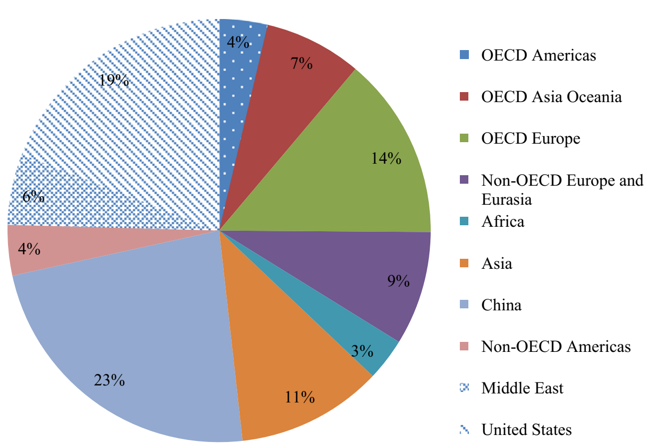

Fig. 1. Global CO_2 emission according to different geographical areas [6].

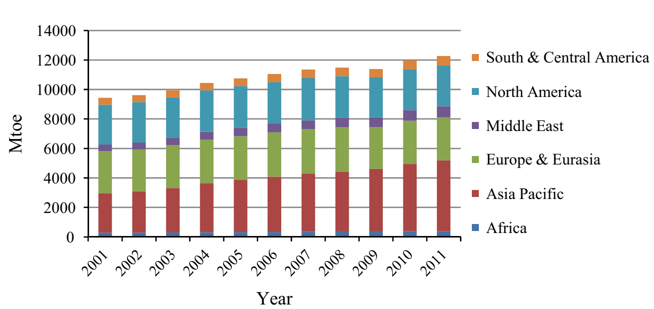

Fig. 2. Cumulative diagram of global energy consumption for different conditions during past decade [10].

Solutions are necessary to address challenges faced by energy sector and also global climate change, and Renewable Energy Sources (RESs) are becoming the most important tools to reduce these negative impacts [11]. Thus, it seems inevitable to use RESs as a way to prevent the increase in fossil fuel consumption and consequently to decrease GHG emissions.

In recent years, renewable energy sources are introduced as the clean energy sources that minimize the catastrophic impacts on the environment caused by fossil fuels. Generally, Sun is the source to all other energy types in the world where its primary energy is light and heat [12]. The Sun irradiation power on the Earth planet is estimated to be about 175,000 TW which is four times greater than the total energy consumption all over the Earth [13]. According to the report released by United States Energy Information Administration (USEIA) in 2011, 13% of the global energy consumption is supplied through renewable energy production. It is predicted that this value will reach 16% by 2040 [14]. RESs include Biomass, Hydroelectric, Sun, Geothermal, Wind and Marine energy sources. Another name chosen for RES is alternative energy sources [15,16]. According to intergovernmental panel on climate change report provided in 2012 [17], the large-scale hydroelectric energy supplies 2.3% of total energy needed all around the world. It is expected that RESs will supply about 30–80% energy by the year 2100 [18]. The increase in contribution of RESs to meet energy demand results in sustainability and improving energy procurement security. Furthermore, Energy Efficiency (EE) enhancement is the main objective of global energy policies to lower the GHG emissions. Moving toward RES has been started since oil crisis of 1970s which had led to rise in prices [19]. In these conditions, some countries specifically in Europe increase the RES operation up to 7–10% that will reach 20% by 2020 [20]. The most important factors causing motivation to use RESs more in comparison with conventional energy sources are reliability, maintenance, accessibility and desired environmental impacts [21]. The total energy provided by RESs was about 12.89% of total energy produced in the world in 2006 of which about 80% belong to Biomass energy. In 2003, this value was 17.6% with more than 90.3% hydroelectric energy [22]. In developing countries like Iran,

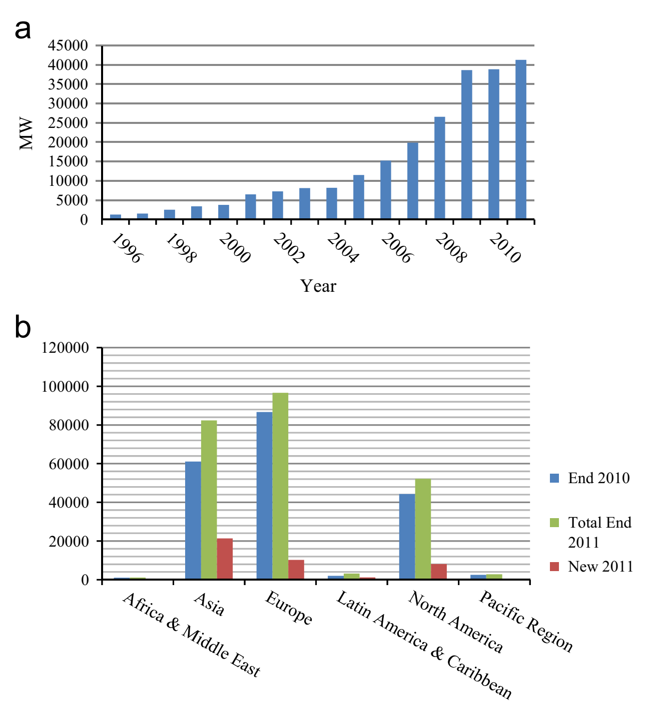

Fig. 3. Installed wind power capacity in the world [23]. (a) During 1996–2011 (b) by the end of 2011.

the RESs contribution to energy production is only about 1% denoting the low participation of these types of energy. Another type of RESs with high potential of producing clean energy is wind power generation. In recent years, researchers have been interested in energy production using wind technologies due to increasing installed wind capacity in certain countries. Fig. 3(a) and (b) illustrates the total installed wind power capacity during 1996–2011 and by the end of 2011 for different regions, respectively. As it can be observed from Fig. 3(a), the installed wind power capacity had been exposed to a dramatic increase during 2004–2009 while over 2010 and 2011, this rate dropped. Fig. 3(b) depicts that Europe is pioneer in the case of installed wind power capacity in comparison with other continents. Asia stands on the second place after Europe. Africa and Middle East have the least share of installed wind power capacity showing that there must be a great investment in these places to exploit the potential sources. It is worth mentioning that Asia has the most amount of installed wind power capacity moving toward the first place in the near future.

The total installed wind power capacity in Iran was about only 10,800 kW in 2001. This value reached to 89,830 kW in 2008 [23–25]. The statistics show that by 2012 this value becomes 91 MW [26]. Since the wind power density is not uniform, it can be used when the energy produced by other energy sources is not sufficient [27]. That is because of intermittent and uncertain feature of wind energy the deterministic models no longer are applicable for wind energy.

Among RESs, wind energy is known as the most uncertain source of energy. On the contrary, stochastic approaches can sufficiently cover the uncertainty problem caused by wind power generation. The volatility of wind power influences the Economic Load Dispatch (ELD) and makes it complicated leading to decrease the system security [28–31]. As wind power generation cannot be accurately estimated, wind farm integration may cause serious challenges for the system operators as a new case of uncertainty in power generation. Therefore, the uncertainties of wind power should be considered in operation of power systems [32]. It is noted that the investment cost of wind power is decreasing rapidly. Moreover, increasing concerns about environmental issues makes governments to establish additional tax and apply restrictions on carbon production. Furthermore some activities are performed such as Renewable Portfolio Standards (RPS) and Regional GHG Initiative (RGGI) to extend the deployment of RESs [33–36].

2. Wind intermittency

Nowadays, because of the main role of RESs in reducing emissions, most countries all across the world are motivated to invest in this sector specially to produce electric energy by wind turbines. Wind power generation has intermittent nature i.e. the power generated is a function of wind speed. In these conditions, the system operation would include an additional cost known as intermittency management cost. The variability model of wind can be utilized to lessen this cost [37,38]. Analyzing the volatile nature of wind generation in planning and operation of power system requires complicated tools. Wind intermittency refers to the unavailability of wind for a remarkable period and volatility declares the smaller, hourly oscillations of wind due to intermittent feature. Some features of power systems such as voltage, frequency and generation adequacy might be affected by volatile and intermittent wind generation leading to vulnerability of power system [39]. Although wind is an intermittent source of energy, it can be considered as a reliable one in long-run [40].

2.1. Wind prediction procedure

If wind speed variation can be predicted precisely, the operational cost of wind generation system would noticeably decrease. This happens if only there would be conventional generating units with high degree of flexibility to manage the variations. The wind power predictions depend on various parameters such as wind speed and direction, air density as well as spatial/temporal scales of atmospheric motion. These problems caused by wind power forecast uncertainty impose a cost to be balanced. Temporal scales are very significant in allocating system reserve requirements. For small time periods of several seconds to several minutes, if the output power of each wind farm is remarkable, the variation of total output power would be small. The uncertainty level in wind power forecast is influenced by several factors as follows: (1) The time elapsed in continuous forecast, (2) Wind power penetration level and (3) The variety of wind power data. This issue would not be different for a single wind farm and/or several ones located in distinct points of the system. It is clear that the forecasted wind speed in four hours ahead is more inaccurate than that forecasted 1 h ahead [41–43]. The power generated through wind turbines is affected by some factors such as, wind speed and direction, turbine position and size, dynamic performance of the generator as well as the wind distribution among parallel turbines where the wind power output is mainly proportional to the wind speed [44]. There are generally two approaches to forecast wind speed as follows: (a) Direct transformation approach, (b) Influencing factors as independent variables. In the first method the wind turbine power curve is used. The validity of this method depends on several constraints. The power curve presented by manufacturer is generally derived from the hub height of wind turbines with known dynamics of wind. It should be assumed that wind flows horizontally and uniformly through the turbines. As these constraints are not always met, using this method does not lead to a suitable estimation declaring the actual conditions of wind turbine operation. In the second approach, the influencing factors are taken as independent variables in a forecasting model to predict the wind power. This approach would be more appropriate in predicting wind power generation. Other influencing factors such as turbine characteristics, direct dependency, site contour, etc. may affect the model structure. Incidentally, constraints such as the measurement height or the profile of the flow are not much significant in direct transformation method. In addition, this method is efficient when measurements through all turbines are not available easily. For instance, the current information is collected from limited numbers of meteorological weather stations [45]. Most researchers are attempting to find an efficient tool to predict the wind power with high degree of accuracy. These tools are categorized into four groups based on their inputs: (1) Physical approach that uses meteorological and topographical information, and also technical features of wind turbines, (2) Statistically exploiting explanatory variables and online measurement such as recursive least squares, (3) Artificial Neural Network (ANN) method, (4) Combination of three above-mentioned approaches [46]. The simulation approach highly depends on the number of scenarios. The first step in this method is to perform Numerical Wind Prediction (NWP) and continues with analytical methods for local wind pattern prediction. While, in the statistical methods, the first step is again NWP and proceeds on statistical ANN or fuzzy logic approaches to calculate the amount of intermittent wind power on the hourly basis where large data sets are required and wind data spikes are difficult to be forecasted. As the wind power can only be predicted over a limited range which is inaccurate, the forecasted values may differ from the actual one. However, the wind power prediction and the accuracy has significant effect in the power system operation [39,47]. Wind has Kinetic Energy (KE) which is proportional to the air mass and the cubic of wind speed. The following equation states the total KE of wind passing through an area at a specified time [40]:

$$P_w = \frac{1}{2}\rho A v^3 \tag{1}$$

where, P_w is the total output of wind power, ρ is the air density, A is the sweep area through which wind passes, and finally v is the wind speed. It should be noted that only a fraction of the total available power (P_w) can be generated by wind turbines. As a result, deterioration in wind speed forecast and measurement appears in the output as a cubic value [48,49]. The wind speed data is the most important input to predict the potential of a wind site due to the cubic relation between wind power and speed. Because of atmospheric system terrain and also the height from the sea level, the wind speed is not uniform in different areas. Wind speed varies hourly, daily, seasonally or even annually. The annual prediction of wind speed requires ten years data collection. Despite a reliable margin in long-term forecasting of average wind speed, it is costly and generally there is no such a long time period in projects to run. In such situations, the short-time data is compared to the long-time one to predict the annual wind speed data. This technique is known as measure, correlate and predict [50]. The Probability Density Function (PDF) of the error forecast values is derived through predicting wind generation and calculating the corresponding error forecast values. This procedure is implemented for predicting the wind generation and also modeling the uncertainty of a wind farm intending to take part in the energy market. This PDF and the hourly forecasted values of wind power would be applicable in scenario generation showing the forecast uncertainty. This method exploits ANN to predict wind power in short-term [51]. So far, several methods have been presented on the basis of Weibull distribution function to determine the capacity of Wind Turbine Generators (WTGs) using Normalized Power (P_N) and Capacity Factor (CF) and also product of P_N and CF under different values of tower height and wind speed. The aforementioned function is utilized to denote the probability of wind speed variations wherein significant relationship between Mean Wind Speed (MWS), wind speed standard deviation and also shape parameter and scale factor of Weibull distribution function are all extracted [40]. Weibull distribution function has been exploited in several typical sites to observe the hourly change in MWS [52–54]. Since year-to-year prediction of MWS is very difficult based on annual horizon, the wind speed variations over a year can be well expressed with PDF. Rayleigh distribution function is another general distribution function used to describe the instantaneous variations of wind speed [40]. The probability functions that frequently use for probabilistic analysis of wind power are defined below.

Rayleigh distribution function: The least complicated PDF employed to describe the wind speed is Rayleigh because it is only needed for MWS to be known denoted as $\overline{U}$. PDF and Cumulative Distribution Function (CDF) can be stated as follows:

$$p(U)=\frac{\pi}{2}\left(\frac{U}{\overline{U}^2}\right)\ \exp\left[-\frac{\pi}{4}\left(\frac{U}{\overline{U}}\right)^2\right] \tag{2}$$

$$F(U)=1-\exp\left[-\frac{\pi}{4}\left(\frac{U}{\overline{U}}\right)^2\right] \tag{3}$$

Fig. 4 shows the Rayleigh distribution for different wind speeds. The Rayleigh distribution is a specific case of Weibull distribution with shape parameter equals to 2 [55].

PDF: The sequence of wind speeds occurrence can be well described using wind speed PDF ($p(U)$). The PDF may state the probability of wind speed between U_a and U_b.

$$p(U_a \le U \le U_b)=\int_{U_a}^{U_b} p(U)\,dU \tag{4}$$

CDF: The cumulative distribution function ($F(U)$) represents the probability of the time at which wind speed is equal or smaller than a specific value, U. That is

$$p\,(U)=probabilit\,y\ \ (U' \le U) \tag{5}$$

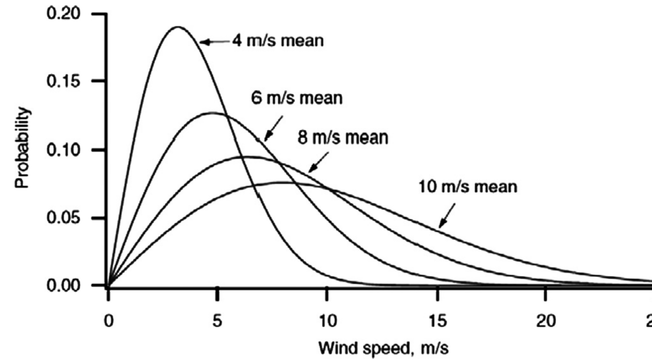

Fig. 4. Rayleigh distribution for different wind speeds [55].

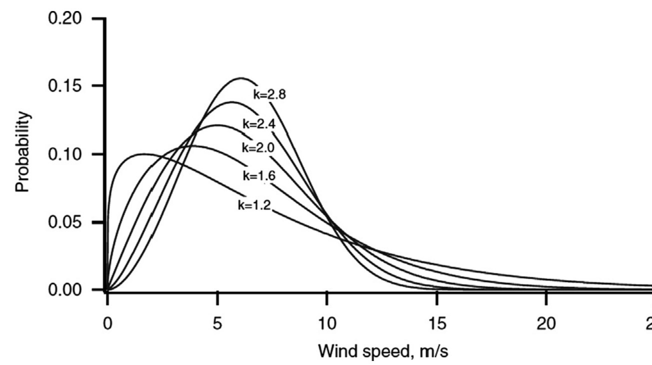

Fig. 5. Weibull distribution for different wind speeds [55].

where, U' is a dummy variable. Also, the derivative of CDF would be equal to PDF as stated below:

$$F\,(U)=\int_0^U p\,(U')\,dU' \tag{6}$$

Also, the derivative of CDF is equal to the PDF

$$p\,(U)=\frac{dF\,(U)}{dU} \tag{7}$$

Weibull Distribution Function: Using Weibull PDF requires fundamental parameters of this PDF to be known i.e. shape parameter (k) and the scale factor (c). These two parameters are functions of mean speed average ($\overline{U}$) and the standard deviation (σ_U). The Weibull Density Function (WDF) and CDF are defined as below [40,50,55,56,57]:

$$p\,(U)=\left(\frac{k}{c}\right)\ \left(\frac{U}{c}\right)^{k-1}\ \exp\left[-\left(\frac{U}{c}\right)^k\right] \tag{8}$$

$$F\,(U)=1-\exp\left[-\left(\frac{U}{c}\right)^k\right] \tag{9}$$

Fig. 5 shows the Weibull distribution for different wind speeds and different shape parameters.

In [55], a new method is used called Here-and-Now Approach in which the wind intermittency is modeled through bringing the probability of stochastic wind power into the model as a constraint that is in the opposite of scenario-based stochastic simulation. An algorithm is presented in [39] in which the wind intermittency and volatility are well characterized. The simulation results on 6-bus and 118-bus IEEE test systems show that the physical constraints of generating units such as ramp rate would be very significant for wind power volatility accommodation. Authors claim that their proposed algorithm is applicable in day-ahead

power scheduling and also in long-term wind units operation in a constrained wind/thermal power system. The intermittent feature of wind power leads to severe challenges in optimal reserve scheduling and also the generation ramping ensuring the reliable load supply. Moreover, the additional reserve must be coordinated with generation ramping to rapidly respond to wind generation intermittency. There are several solutions to this problem such as employing storage systems or extra power transaction with adjacent power systems as well as using conventional generation systems with fast response like gas units [58–60]. The main contribution of this paper is to introduce systems with ability to rapidly respond to wind power generation and cover the wind power intermittency. Thus, energy storage systems such as Pumped-Hydro Storage (PHS) units, solar units, electric vehicles with ability to connect to the electric grids (PEVs and PHEVs), battery storage systems and also fast-response units will be discussed in the following sections.

3. Wind with pumped hydro storage

The wind power generation is a function of wind speed leading to wind power intermittency and volatility. Furthermore, the uncertain nature of wind power generation results in introducing average wind speed, local winds prediction, etc. In order to manage and compensate the uncertainty and intermittency caused by wind generation, several solutions are presented. Using pumped-storage units would be one of these solutions to wind intermittency compensation. A pumped-storage unit constitutes several components such as a pumping station, a turbine station, two water reservoirs installed at different heights and also piping lines. Usually, there are water pumps installed in parallel to absorb the fluctuation in power caused by RESs [61,62]. PHS is the oldest type of large-scale storage systems since 1904 which has been still used and new ones are under construction all around the world [63]. Iran is pioneer in building dams where most recently a large pumped-storage unit has been built on Siah-Bisheh located in the northern Iran. The study on this project started in 1970 while it was finished in 2012. The capacity of this unit is 1000 MW that virtually supplies 1/40 of the total power demand in Iran. Its upper reservoir has the capacity of 4.3 million m^3 and the lower reservoir contains more than 6.9 million m^3. The main objective beyond building this pumped-storage unit is to balance the variations in load and also stabilize the north area of Iran power system [64]. The popularity of pumped-storage units is due to its individual features such as, capability and flexibility in rapidly responding to load variations or spot energy price [63,65–69]. The pumped-storage owners are able to participate in competitive electricity markets to trade their productions. The pumped-storage units operate in two modes: generating mode and pumping mode where the incomes obtained by pumped-storage units comprise selling energy in the generating mode or taking part in A-synchronous reserve market both in generating and pumping mode. Also, pumped-storage units can take part in synchronous reserve market of pumping mode, because it reduces the demand of the power grid due to the reduction in their required pumping energy. According to what mentioned above, there are motivations for optimal scheduling of the pumped-storage units in restructured power systems. In vertically integrated utility power systems, the coordination of hydro-thermal units was performed with the aim of reducing fuel cost and emissions using PHS to supply the peak load and pumping the water back into the upper reservoir in light-load periods. In restructured power market, PHS owners are able to trade their energies in day-ahead and spot electricity markets or through bilateral contracts. The liberalization progress causes fundamental changes in power system operation and management. In competitive power market, power producers encounter with severe challenges in maximizing their profit [65,70–72]. Most recently, researchers investigate the issue

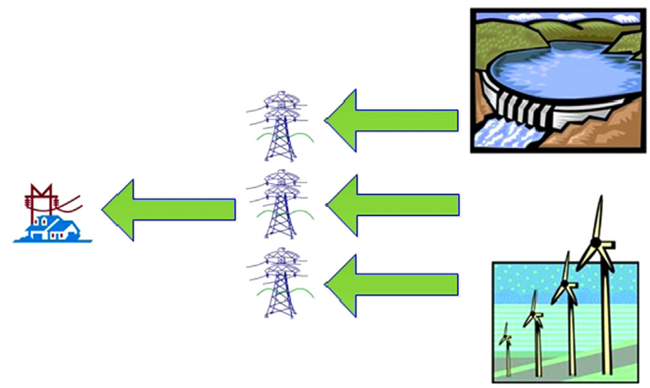

Fig. 6. A simple scheme for compensating wind intermittency using pumped-storage unit.

of compensating the wind power intermittency production by employing modern technologies. A simple scheme to exploit pumped-storage units as wind intermittency compensator is expressed in Fig. 6. Also, a model is proposed in [73] to economically evaluate the hybrid wind/PHS technology wherein the market model of Germany and Norway is used as the case study considering all uncertainties effective on the investment decisions. The uncertainty considered in this research is due to the increase of electricity price and also the effects of newly installed capacities on the market condition. Therefore, PHSs are recommended by authors to solve the problem and also increase the profit of wind power generation.

In order to improve the current conditions of wind energy integration in Greek islands, wind power generation along with a PHS unit is suggested in [74]. The proposed hybrid station is considered as a constant-rate generation unit paralleled with several wind turbines delivering a sufficient power to the electric grid in peak hours. The possibility of integrating wind for an isolated electric grid is investigated wherein the operational parameters of PHS system are determined exploiting an integrated calculating algorithm to supply the electric energy on the basis of daily horizon. The most common and the best way to overcome the problems caused by wind power generation in isolated networks are utilizing hybrid hydro/wind schemes [62,75–82]. That is the most appropriate way to optimally and desirably operate the available wind power capacity with high degree of penetration for small islands with low installed capacity is to use PHS units [62]. The PHS has been considered as a large storage system installed more than 95 GW all across the world, generally to promote the wind power integration to supply base load [83]. The need for exploiting PHS unit would be obvious through comparing the local networks demands to corresponding annual wind farm efficiency [81]. A novel strategy is proposed in [51] for Self-Scheduling (SS) of integrated wind farm and PHS unit. In the suggested strategy, a Generation Company with both wind farm and PHS unit is responsible for integrated SS of both units with respect to the wind power uncertainties. In order to achieve this goal by GENeration COmpany (GENCO) and obtain more benefits, GENCO participates in energy and ancillary service markets. In the presented strategy, the PHS unit is able to take part in regulation and spinning reserve and a technique is proposed based on ANN using a new distribution function to model the wind power uncertainty wherein the problem is modeled as a MINLP optimization problem. As mentioned above, one of the most common ways to increase the obtained profits by wind units is to utilize hybrid scheme of wind/PHS units. The coordinated operation of wind/PHS unit leads to an appreciable profit for wind farm participating in the markets compared to the only wind operation while the capability of PHS unit to store energy decreases the SS

risk for wind power units in the market. The integrated SS of hybrid wind/PHS units requires the participation of PHS unit in the ancillary services and energy markets, if not, the obtained profit would not be estimated precisely [84,85]. An influencing factor in integrated SS is modeling the wind generation uncertainty. The risk faced by wind power producers would increase without considering this uncertainty [86,87]. The most significant reasons of using PHS with wind power generation would be as follows:

- Use of PHS unit increase load during light-load periods and causes the increase in penetration of RESs.
- PHS unit is considered as a low-priority load in load scheduling program during pumping mode and can be curtailed in primary levels [88,89].
- The surplus wind generation can be consumed to pump and store water in upper reservoir [61]. In these conditions, the stored water in the upper reservoir can be used to produce electric energy during peak hours leading to the added value for PHS unit. The released water to generate electric energy can be returned to the upper reservoir from the lower reservoir during light-load periods to decrease the costs in pumping mode.
- PHS unit can be used as water storage for residential and agricultural goals and also used during fire.

In addition, such system can be utilized to encounter climate change through enhancing the electric system stability or producing clean water in desalination plant [62]. It is expected that PHS unit turns into a common tool in near future to reduce the intermittency and volatility of RES energy in the electric networks. Furthermore, other technologies can be useful in integrating wind power generation such as thermal storage using thermal pump or boilers due to their flexibility and capability of storing energy from volatile energy sources [90].

4. Wind with PHEVs

Since the forecasting of wind speed and the time when wind blows is too difficult due to the fact that wind speed is an uncertain parameter, wind power generation would be stochastic. This section investigates the compensation of wind power intermittency employing Plug-in Hybrid Electric Vehicles (PHEVs). This type of vehicles is environmentally compatible vehicles. The car manufacturers started working on Electric Vehicles (EVs) projects such as Plug-in Electric Vehicles (PEVs), Hybrid Electric Vehicles (HEVs), PHEVs and fuel-cell vehicles to meet their demand in case of producing vehicles with lower emission [91]. As mentioned above, in order to overcome the environmental issues caused by fossil fuels and producing CO_2 and also to prevent GHG emission propagation in the world, PEVs and HEVs were firstly produced. HEVs have encountered a fundamental problem in comparison with PEVs in the case of changing their batteries merely through burning fossil fuels. Therefore, PEVs have too many advantages from the environmental viewpoint such as zero dispersed emission, low operational costs and their independency on fossil-fuels. However, HEVs are not able to connect to the grid [2,92] and out of scope of this paper. The aforementioned advantages make PHEVs the best alternative for replacing conventional vehicles with fossil fuels. Thus, in the next, some unique features of this vehicle will be discussed. One of the most important parts of each PHEV is the Energy Storage System (ESS) [93–101]. The most common ESS is battery. The relative deficiencies of electrochemical energy storage compared to conventional fuels are in the case of their limited energy, low energy density and low changing rate [102]. PHEVs exploit both electrochemical energy storage system and conventional fuels to overcome the previous systems' disadvantages and also provide additional benefits for customers and the society. In modern PHEVs, the difference between electric mode, charge-depleting mode and the charge-sustaining mode is almost non-sensible to the driver. These factors permits PHEVs to use electric energy instead of fossil fuels in transportation system having advantages such as increasing the energy efficiency of the transportation system, reducing CO_2 emissions, reducing emission criteria and fuel cost, and improving transportation energy sector sustainability [103]. Moreover, PHEVs have other applications such as working as storage systems in the electric system particularly, performing as the storage to decrease the RESs' intermittency. PHEVs have become one of the most interesting factors among policy makers, automobile manufacturers and also electric utilities. The researches show the remarkable market for PHEVs [102]. PEVs are also able to connect to the electric grids. This ability of PEVs makes them able to balance the uncertainties caused by RESs. The PEVs' contribution to enhance the intermittent RESs integration in the electric grid depends on technical factors such as storage capacity, the capacity connected to the grid and the driving behavior. The above mentioned issues determine the available energy for load shifting and also influence the economic and social aspects of participating in load shifting program [104]. PHEVs and PEVs are able to balance the variations of thermal units loading through altering the grid load profile and also providing an appreciable storage to the system. This storage is supplied via batteries of PHEVs and PEVs. The most influencing factors in changing the load profile of the network by PHEVs are the load demand and the number of PHEVs and also choosing a proper strategy for this goal [105]. PHEVs and PEVs connect to the electric grids via a conductive charger to bi-directionally exchange power [106]. This mode provides more dispersed generation in addition to applications in Demand-Side Management (DSM) that is the capability of future EVs [99,107]. PHEVs and PEVs have two operating modes. The first mode is named as Grid-to-Vehicle (G2V) mode in which electric power flows from the electric grid to the EVs (PHEVs and PEVs) to charge the batteries. In this situation, EVs are considered as load. The second mode corresponds to the connection of EVs to the electric grid to act as a dispersed generation delivering electric power to the grid. This mode is called Vehicle-to-Grid (V2G) [106,108—110]. Similar to other energy storage systems, EVs (PEVs and PHEVs) are charged during light-load period and sell their stored energy during peak hours. The V2G mode has several advantages. The most significant one is electric vehicle with lower emission but remarkable if the electric grid is supplied by RESs. Other utilities would be as follows:

- Enhancing stability
- Improving reliability
- Low electric system's cost
- Presenting worthwhile storage and back-up for intermittent RESs [110–112].

In [113], the roles of PHEVs and Demand Response (DR) for wind intermittency and variability are discussed. PHEVs and DRP are able to rapidly balance the wind power intermittency through regulating the consumption of end-use consumers. This rapid regulation can improve the system load profile. Thus, a novel UC model is proposed in [113] to simulate the interaction between PHEVs, wind power and DR. In [114], an optimization tool is presented to analyze and model the power system expansion of North-Eastern Brazil having the capability to efficiency plan the wind farm production going to be constructed in 20 years. Thus, the main purpose is compensating the imbalance caused by wind power generation using North-Eastern Brazil PHEVs fleet where there are conventional inflexible generating units. Besides, the

possibility of using variable generating units in long-term is investigated through employing optimization tools such as Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE). In [115], an optimization tool is suggested to minimize the cost and expected emission in the UC using PEVs with uncertainty through set of scenarios wherein the presented results show the efficiency of smart grid potential in maximizing RESs penetration and employing PEVs to reduce cost and emission in power systems as well as in the transportation sector. These two sectors are the main sources of GHG emissions. A model to coordinate PEVs and RESs such as wind energy in power system is presented in [116] exploiting stochastic Security-Constraint Unit Commitment (SCUC). In the proposed model, the operation cost of electric system is minimized considering PEV's random behavior. Authors in [117] have employed a new model for Probabilistic Constrained Load Flow (PCLF) to be used in modern power systems while the wind intermittency and PEVs' uncertain nature are taken into account.

5. Wind with solar

Wind and solar energies have several unique features such as being interminable, zero-emission, site-dependant as well as being the alternative energy options. The energy production by wind and solar sources generally depends on climate conditions where the highest level of energy injection to the electric grid occurs during the high energy price. One of the most common systems used to co-operate wind and solar energy is hybrid wind/solar Energy Conversion Systems (ECS) using two RESs. The system efficiency and the output power reliability are improved through using this system while the storage and reserve requirements are decreased. The output power of a hybrid ECS cannot be dispatched normally by system operators, since it depends on several external natural factors varying in a wide range. The main limitation faced by wind and solar energy generation are their intrinsic variability and also dependency on climate conditions [118]. One of the advantages obtained through employing hybrid ECS would be the reduction in output power fluctuations in addition to the increase in power generation, i.e. energy storage and reserve necessities can be appreciably diminished [119]. A systematic stochastic programming framework is proposed in [118] to integrate wind and solar energy sources in which stochastic variables are wind and solar power outputs. In order to model the uncertainties, Weibull and Beta distribution functions are used to model the wind speed and solar irradiation wherein required parameters to define stochastic models are calculated from site-specific data utilizing maximum likelihood estimation approach. The design and simulations of three energy sources i.e. wind, solar and PHS are performed in several works. In [120], the battery storage system is replaced with a PHS in a hybrid wind/solar energy system having the ability to overcome intrinsic problems of hybrid system as well as the problems caused by load imbalance due to wind and/or solar uncertainties. Since, wind and solar power generations are uncontrollable factors not being accessible continuously, they are called intermittent energy sources. In some areas, these intermittencies can be predicted to some extent from previously recorded data. However, wind speed and solar irradiation forecasting are involved with a certain degree of uncertainties. In [121], wind and solar power and also system demand are considered as stochastic parameters in order to determine the optimal combination of wind and solar capacities. Furthermore, a novel formulation is presented to determine the optimal size of wind and solar system in which, authors intend to maximize the system reliability with respect to fixed monetary capital cost of wind and solar. The proposed model is formulated as Mixed Integer Programming (MIP) optimization problem wherein the uncertainties concerning with hourly demand, wind speed and solar irradiation and also the possible generation system failures combinations are all taken into account. In [122], a systematic analytical method is proposed to assess the well-being of Small Autonomous Power Systems (SAPSs) including wind and solar energy source. The one-year planning horizon is separated into several periods which are considered independent in order to eliminate the correlation between solar and load. Generally, this procedure is performed using statistical correlation analysis of solar irradiation and demand of consumers from past data [123]. Moreover, the impact of wind power variations on system stability is restricted by considering wind power generation as a small portion of the system demand. To implement the generation scheduling problem using conventional approaches, the hourly demand for power balance, the available water for hydro units and solar irradiation for photovoltaic units must be predicted to prevent errors. Nevertheless, there are always errors in the predicted values. In this regard, an optimization framework is presented in [124] based on fuzzy sets which can be efficient to achieve a desired generation scheduling in hourly basis for the available water, wind speed and the solar. Operation of wind and solar technologies alone or interacting with the electric system is of interest of system operators for their sustainability and reliability. However, research on wind and solar technologies to optimize their functions and develop suitable techniques to precisely predict their output powers is required to be carried out for these sources [123]. Ref. [125] has investigated the frequency control support of a French island with ESSs using dynamic simulation. This island exploits great contribution of wind and solar power generation. It is stated that utilizing fast-response ESS acting as synthetic inertia would lead to mitigation of negative impacts of wind and solar sources on the dynamic performance of the electric grid of the island. The factors postponing the development of RESs in India have been discussed in [126] while some methods are suggested to eliminate these barriers. The effectiveness of wind and solar energies to serve the peak load in North-Eastern Brazil is addressed in [127]. Ref. [128] discusses the fundamental problems of electricity generation in a small island using RESs while integrating ESSs are considered as a solution to these problems.

6. Wind-battery

The variable nature of wind farm leads to severe challenges for system operators. This uncertainty can be compensated using fast response dispatchable sources such as gas turbines or hydro units. However, employing dispatchable sources to cover the wind power volatility causes to increase cost of wind power integration in short-run due to the increase in system required reserve. In addition, using hydro generators to track load demand to balance the mismatch caused by wind power prediction error results in earlier maintenance program [129]. One solution to exploit the wind power generation is utilizing small rechargeable battery bank consisting of one or two groups of batteries installed in the wind turbine tower. Nowadays, energy storage systems have become an applicable option to be included with wind power. For investigating the dynamics of wind power generation with battery storage system, the information about the wind speed variations must be accessible in addition to the steady-state models of batteries, generators, convertors and transformers, and electric power system that are rarely available. There are lots of rechargeable batteries with various features and prices and lifetime cycles. For instance, lead acid batteries have the lifetime of about 5–10 yr in the normal temperature. Another type is

capacitor batteries using super-capacitors to store and release the electric energy. Super-capacitors have the ability to be quickly charged or discharged including electro-chemical cells to store the electric energy. The most recent development in this area is called nanotube super-capacitor battery. The most significant factor in utilizing batteries is their costs [130]. ESSs have been used for three purposes: power levelling enhancement, improving bridging power and power quality. Thus, Reference [131] proposes a detailed analysis of BESS's electric features to calculate the charge/discharge time of batteries. In this scheme, two BESSs are considered where the generated power by wind turbines is used to charge one BESS while the other one is used to discharge power into the electric grid at a fixed rate. For far residential areas with small demands, stand-alone wind power generation along with a battery bank as energy storage are used that are necessary for sustainable and reliable supply [94,132]. For this system, load is a battery which can be considered as energy sink with almost fixed voltage while it is able to absorb power at any level until the charging current is in range. Since, voltage is almost constant and the current would vary, the battery can be considered as a variable-resistance load [95,96].

7. Other storage systems for wind

It is worth mentioning that there are also other types of storage systems applicable to wind power system. This part investigates these storage systems as follows.

7.1. Wind-diesel engine

Another possible topology to compensate the wind intermittency is to use Wind-Diesel Hybrid Systems (WDHS). WDHS systems are defined as any autonomous electric energy generating units in which WTGs associated with Diesel Generators (DG) are employed together to maximize the contribution by the intermittent wind power production to the total generated power while producing continuous power of high quality [133–135]. The main purpose of employing such system is to reduce the operation cost while decreasing the fossil fuels consumption and their negative impacts on the environment. WDHS are available in different types including low, medium and high wind penetration levels. If the annual output energy of wind turbine to the primary annual energy demand is less than 20%, WDHS is known as Low Wind Penetration (LWP) while if this proportion is between 20% and 50%, it is called Medium Wind Penetration (MWP) and if the DGs have the ability to shut down, this system is known as High Wind Penetration (HWP) [136].

HWP comprises three different operating modes including:

- Diesel Only (DO): In this mode, the active and reactive demands are supplied through diesel unit.
- Wind Diesel (WD): In this mode, WTGs also contribute to active power supply.
- Wind Only (WO): The contribution of WTGs to supply the required active power flow is planned while in this operating mode, the fuel consumption and also emissions are considerably less than the aforementioned modes [134,135,137,138].

In LWP system, the investment cost is remarkably high causing them not to be economic while using HWP systems would lead to a noticeable profit and less fuel consumption. It is worth mentioning that these systems are not able to capture all electric power produced by WTGs operating at their rated capacity [139]. The performance of HWP units along with Compressed Air Energy Storage (CAES) is investigated in [140]. The economic advantages of employing Wind-Diesel CAES units are started and the results are proposed taking into consideration their potentials to reduce the fossil fuels while raising the efficiency. The model presented in [141] is based on real option theory assessing a Hybrid Wind-Diesel unit. The problem has been modeled as an optimization problem with the objective to maximize the net cash flow of the hybrid unit using Dynamic Programming (DP) in order to find the optimal operating point. Ref. [142] has proposed a software to schedule the coordinated generation of Wind-Diesel unit assessing the additional cost needed to cover unpredictable variables in power output of wind generators. Furthermore, this software can be utilized to forecast the energy cost and fuel saving of such unit.

7.2. Wind-compressed air energy storage

As mentioned above, using some methods to reduce the wind intermittency seems inevitable. In this regard, one of the methods introduced to eliminate or at least decrease the uncertainty of wind power is employing CAES systems associated with wind units.

CAES can be used with wind generating units to supply almost fixed, dispatchable power. Moreover, this storage system can operate in peak load to improve the electricity price. In CAES systems, energy is stored in a pressure gradient (the amount of charge in a pressure occurring over a fixed distance at a fixed altitude) between ambient air and an underground carven [143]. One of most significant issues with CAESs is their efficiency which is three times more than a simple gas turbine [133].

A CAES system is modeled in [144] to enhance the wind power integration with the objective of profit maximization. This system is independently used for a wind farm in which the profits obtained through spot and reserve markets are maximized. A security constrained unit commitment method is proposed in [133] using ESSs and wind power generation. CAES has been taken into consideration as an alternative for ESS. The suggested model allows the simultaneous optimization of energy and ancillary services considering the ESS.

8. Global statistics of wind power generation

Wind power production has encountered global growth by 6% in 2011 compared to 2010. The increased installed capacity is about 40.5 GW. The wind power generation is almost increasing in all industrial and developing countries. Ten pioneer countries in this area are China, USA, Germany, Spain, India, France, Italy, UK, Canada and Portugal. 200,640 MW out of 238,351 MW wind power generated all over the world are produced in these countries which is equally 84.17% of total global wind power generation [17,26] as shown in details in Fig. 7.

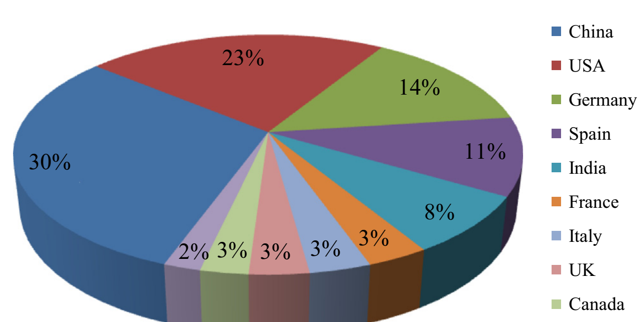

Fig. 7. Detailed wind power generation in 10 pioneer countries [17,23].

Researches show that emission is reduced by 28% during past ten years due to utilization of RESs, particularly using wind power generation instead of conventional fossil fuels. As it can be observed in Fig. 7, more than 50% of newly installed wind capacity in 2011 belong to China and India. Thus, these two countries can be considered as the main players in wind power market all across the world [17,26]. In the following, several pioneer countries in wind power generation are introduced in details:

- *China*
  With respect to the role of China in producing wind power, this country has the first rank among other countries both from aggregated capacity and recently installed capacity viewpoints. China has built wind farms in some areas of North, North-Eastern and North-Western country which are windy locations during recent decades. Statistics express that the total wind power capacity has reached 62,733 MW by 2011 showing 18,000 MW of new capacities installed in 2011 in China. Moving toward decentralized wind power generation has started in 2011 in areas with lower wind speeds. Total wind energy produced in China after 2011 is about 71.5 TWh which is equal to 1.5% of the total generation of China. This matter leads to reduce the emission propagation by 70 million tons of CO_2. It is predicted that by 2020, the total wind power capacity in China will reach 200–300 GW and by the year 2030, the wind power generation will be 400 GW i.e. 8.4% of the total demand in this country [17,26].
- *USA*
  After China, USA is the biggest wind power producer all over the world in the case of aggregated capacity and recently installed capacity. The USA's wind power capacity is about 40,180 MW i.e. 20.4% of the total global installed capacity in 2011. Statistics show that this country encountered with 6018 MW growth i.e. 30% in installed capacity over 2011 in 31 states. In 2011, the total wind power capacity was 46,919 MW i.e. 17% growth in wind power in this country [17,26].
- *Germany*
  Currently, Germany stands in the third rank in the world in the case of total wind power capacity while in 2011 it had the fourth rank in the case of recently installed capacity standing after China, USA and India. In Europe, Germany is the most pioneer country. With respect to this point that the recently installed capacity in Europe was about 10,281 MW in 2011, Germany has 20.3% of total recently wind capacity in Europe [17,26].

9. Conclusions

The intermittent feature of the wind power generation causes some problems in power balance of the electric systems. Considering the uncertainty in wind power generation, some issues like estimating the average wind speed are well discussed where Weibull PDF is introduced to model the wind speed. Besides, some technologies are introduced to solve the uncertainty of wind power such as PHSs to fix the output rate of the wind and also increase the profit. Another technology discussed in this paper is PHEVs which is able to compensate the wind intermittency through utilizing V2G capability. Furthermore, other systems such as hybrid wind/solar scheme and batteries are discussed to compensate the wind uncertainty. Finally, wind power projects in pioneer countries are discussed.

Acknowledgment

This work is supported by the Australian Research Council (ARC) and Essential Energy Linkage Grant, LP100100618.

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